

## Aluminum matrix texture and particle characterization in Al-Al<sub>3</sub>Ti FGMs produced by a centrifugal solid-particle method

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**Abstract** The centrifugal solid-particle method has proved to be effective in producing functionally graded materials (FGMs). In this study, Al-Al<sub>3</sub>Ti FGMs, were produced by this centrifugal method, from an Al-5 wt % Ti master alloy. Applied centrifugal forces were 30, 60 and 120G (units of gravity). Samples from the outer surface of each specimen were cut and aluminum matrix texture analyzed by Schulz reflection method. Analysis of the resulting pole figures indicates a preferred orientation along the (200) plane for the aluminum matrix crystals. Furthermore, increasing the applied centrifugal force enhances the orientation effect. Al<sub>3</sub>Ti platelet orientation and area fraction at the samples' outer surface along three observation planes were also measured. The Al<sub>3</sub>Ti platelets in the outer region are orientated perpendicular to the centrifugal force direction along two of the observed planes, also an increase in centrifugal force leads to an increase in orientation in those two planes. The intermetallic particle volume fraction also increases with higher applied centrifugal force, although not significantly. A correlation appears to exist between particle orientation and the preferred orientation of the matrix.

### Introduction

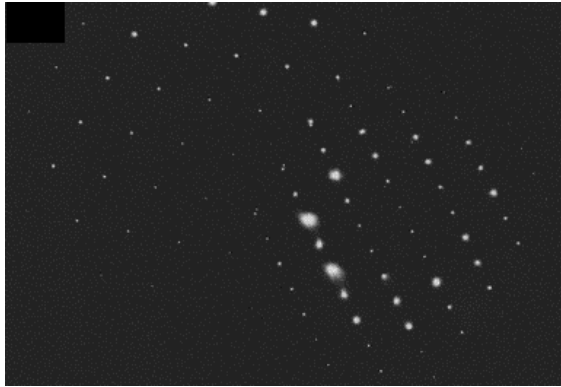
By a centrifugal solid-particle method [1-4], Al-Al<sub>3</sub>Ti FGMs have been successfully produced. In this method the alloy is heated up to a temperature located between its *solidus* and *liquidus* temperatures, where most of the intermetallic platelets remain solid in the liquid Al-based matrix. The density of the Al<sub>3</sub>Ti particles is higher than that of the molten Al matrix. Due to this density difference, upon casting under centrifugal force the Al<sub>3</sub>Ti particles will be segregated in the direction of the applied centrifugal force. This will lead to a graded distribution of the intermetallic particles in the Al matrix [5].

Since the material is composed of two phases its properties depend on the properties of each phase separately as well as on the inter-relationship between those two phases [6]. Furthermore, spatial orientation and distribution of the two phases will also affect the materials properties. In fact, anisotropic wear resistance in an Al-Al<sub>3</sub>Ti FGM has been studied [7].

Also, in a previous study the crystallographic relationship between the Al matrix and the Al<sub>3</sub>Ti particles was studied by transmission electron microscopy (TEM) [8]. Selected area diffraction (SAD) taken along a low index direction provided useful information in determining the orientation between the Al matrix and the Al<sub>3</sub>Ti particles. Diffraction patterns taken at the Al-Al<sub>3</sub>Ti interface are shown in Fig. 1. The orientation relationship between the Al and the Al<sub>3</sub>Ti phases is given by

$$(111)_{\text{Al}_3\text{Ti}} // (111)_{\text{Al}}, [\bar{1}10]_{\text{Al}_3\text{Ti}} // [\bar{1}10]_{\text{Al}} \quad (1)$$

A good lattice correspondence is found for the close packed directions and the close packed planes between two crystals [8]. Therefore, it is expected that, due to the existence of a preferred orientation for the intermetallic particles and the above mentioned lattice correspondence, the aluminum crystal would also exhibit an orientation pattern.



In order to corroborate this notion, aluminum crystal texture was analyzed by the Schulz reflection method [6]. In this study, results concerning the characterization of  $\text{Al}_3\text{Ti}$  particles and the aluminum matrix texture at the surface of produced FGM rings are presented.

Fig. 1 - Diffraction pattern at the Al- $\text{Al}_3\text{Ti}$  interface [8]

### Experimental Methods

Al- $\text{Al}_3\text{Ti}$  FGMs were produced by the centrifugal solid-particle method, from Al-5wt % Ti commercial alloys. Crystal structures and densities are presented in Table 1. Since the relative atomic masses of Al and Ti are 26.98 and 47.88, respectively, the theoretical volume fraction of  $\text{Al}_3\text{Ti}$  in the master alloy was calculated to be approximately 11 vol% [7].

In the centrifugal solid-particle method the alloy is heated up to a temperature located between its *solidus* and *liquidus* temperatures. Therefore, most of the intermetallic platelets remain solid in a liquid Al-based matrix. It is then poured into a rotating mould in order to obtain ring-shaped samples. The temperature of the melting furnace was 1173 K and applied centrifugal casting forces were 30, 60 and 120G (units of gravity). The FGMs rings have an outer diameter of 90mm, 25mm in height and a length of 20-25mm. A detailed description of the centrifugal method is available elsewhere [1-4,7].

Samples were taken from the rings outer region. Optical micrographs were taken and intermetallic particle size, distribution and orientation were measured along three observation planes, perpendicular to the rotating axis (referred as OP1 in the subsequent text), perpendicular to the rotating direction (OP2) and perpendicular to the centrifugal force direction (OP3), as seen in Fig. 2. For quantitative analysis of the Al matrix texture along OP3, pole figures obtained with the Schultz reflection method [6] were used.

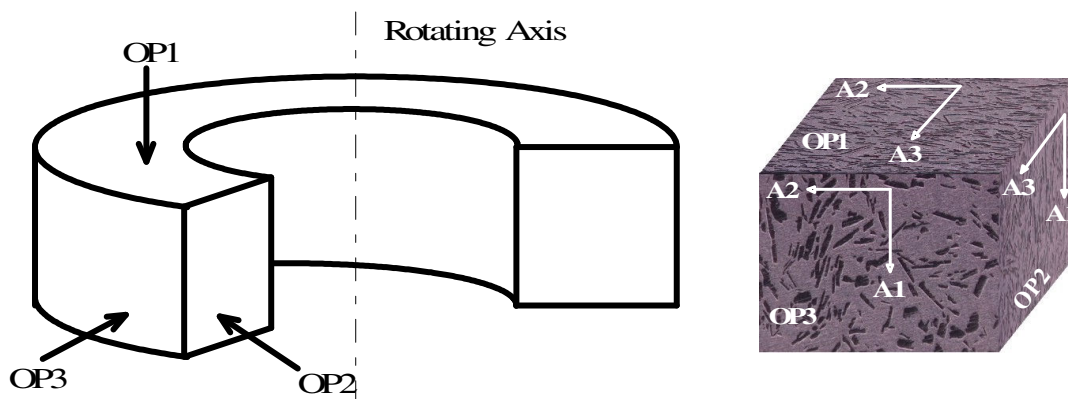


Fig. 2 - Schematic drawing of the FGM ring. A3 is the centrifugal force direction, A2 is the reference axis for OP1 and OP3, A1 is the reference axis for OP2.

Table 1 - Crystal Structure and density

Element or compound	Crystal Structure	Density [Mg/m <sup>3</sup> ]
Al	<i>fcc</i>	2.7
Al <sub>3</sub> Ti	<i>D0<sub>22</sub></i>	3.4

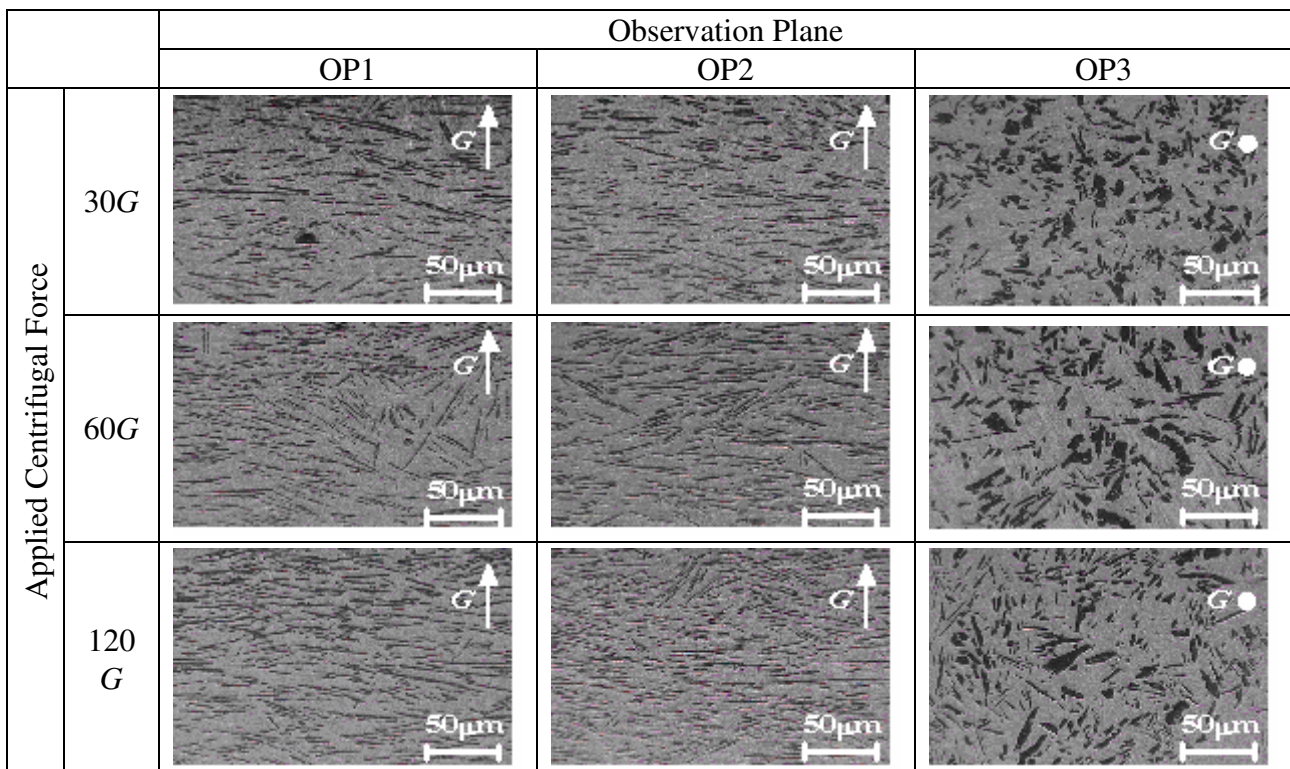
## Results and Discussion

**Characterization of the Al<sub>3</sub>Ti intermetallic particles.** As seen in Table 2, the average intermetallic area fraction at the outer surface increases with higher applied centrifugal force. When comparing the 60 and 120G specimens, there is only a very small increase in the measured area fraction. From this fact it is deduced that the maximum particle area fraction packing is around 23-25%.

As seen in Fig.3, the microstructures along OP1 and OP2 for the three samples are very similar while that is not the case with the observed microstructure along OP3. This is due to the nature of the Al<sub>3</sub>Ti particles and the observation method. Al<sub>3</sub>Ti particles are platelet in shape and they tend to be oriented perpendicular to the centrifugal force direction. OP1 and OP2 intersect the platelets along its edges while OP3 intersects the platelets face.

Table 2 – Area fraction occupied by the Al<sub>3</sub>Ti particles at the surface of the FGM specimens

Applied centrifugal force	Area occupied by the Al <sub>3</sub> Ti particles [%]			
	OP1	OP2	OP3	Average
30G	19.5	22.3	21.58	21.13
60G	22.3	22.6	24.58	23.16
120G	26.0	21.2	22.9	23.37

Fig. 3 - Microstructure at the specimens' outer surface, dark areas are the Al<sub>3</sub>Ti particles

Taking a line perpendicular to the centrifugal force direction as reference axis, the  $\text{Al}_3\text{Ti}$  particles' angle in relation to that axis along the three observation planes was measured. In OP1 the reference axis is the A2 direction, for OP2 it is the A1 direction and along OP3 the reference axis was the A2 direction. Results are presented in Fig. 4. Particles tend to be concentrated between  $-15^\circ$  to  $15^\circ$  angle to the reference axis along OP1 and OP2, while along OP3 no pattern is evident. Although it is not entirely clear by the orientation histograms, an increase in applied centrifugal force leads to a higher orientation effect along OP1 and OP2. To quantitatively express this tendency Hermans orientation parameter,  $fp$  [9,10], is used (Table 3). An orientation parameter of 1.0 expresses a perfect alignment of the particles with the reference axis and  $fp = 0.0$  a completely random dispersion of particles. Negative values indicate a tendency for the particles to be aligned perpendicularly to the reference axis.

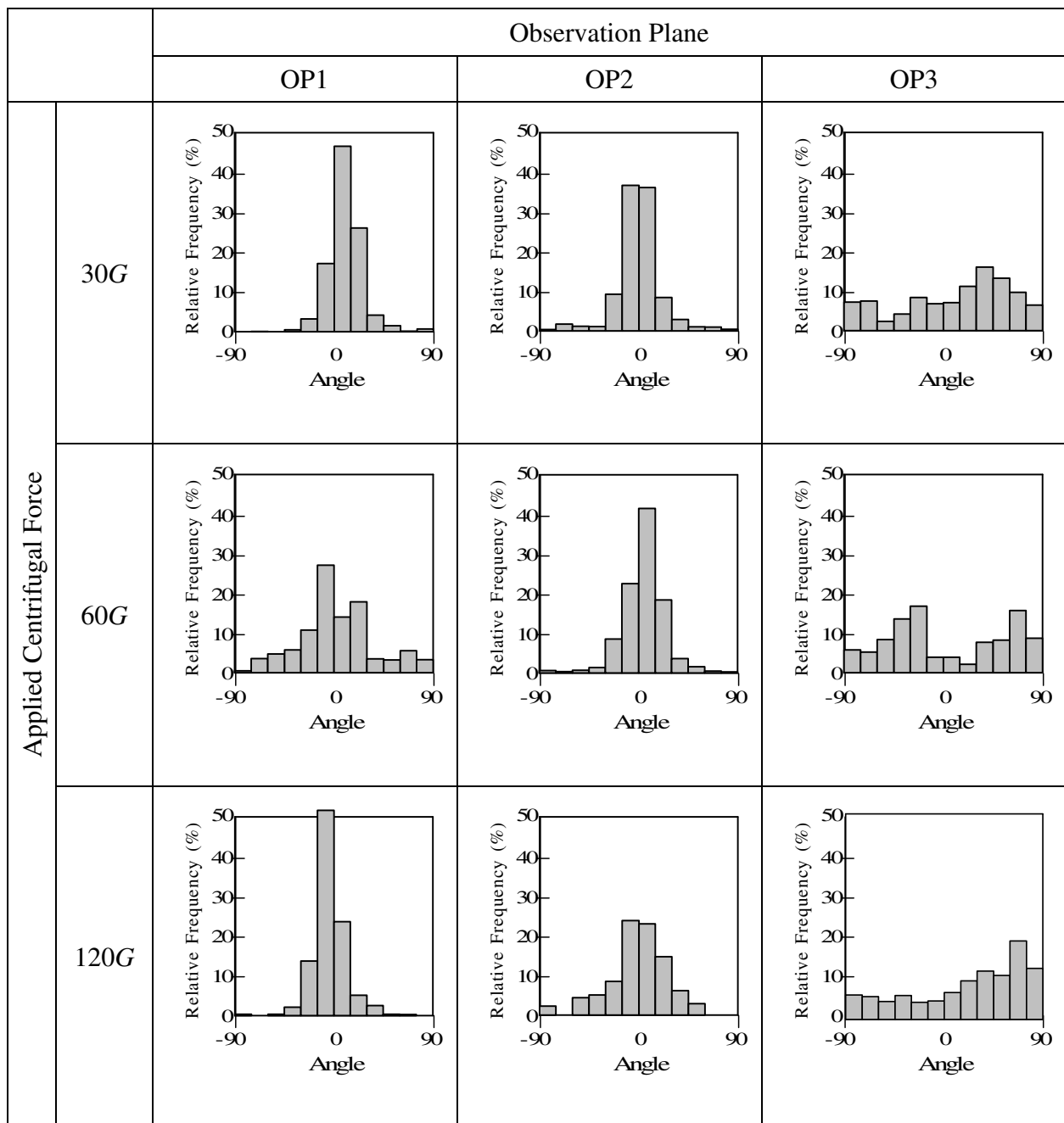


Fig. 4 - Orientation Histograms for  $\text{Al}_3\text{Ti}$  platelets at the samples' outer surface

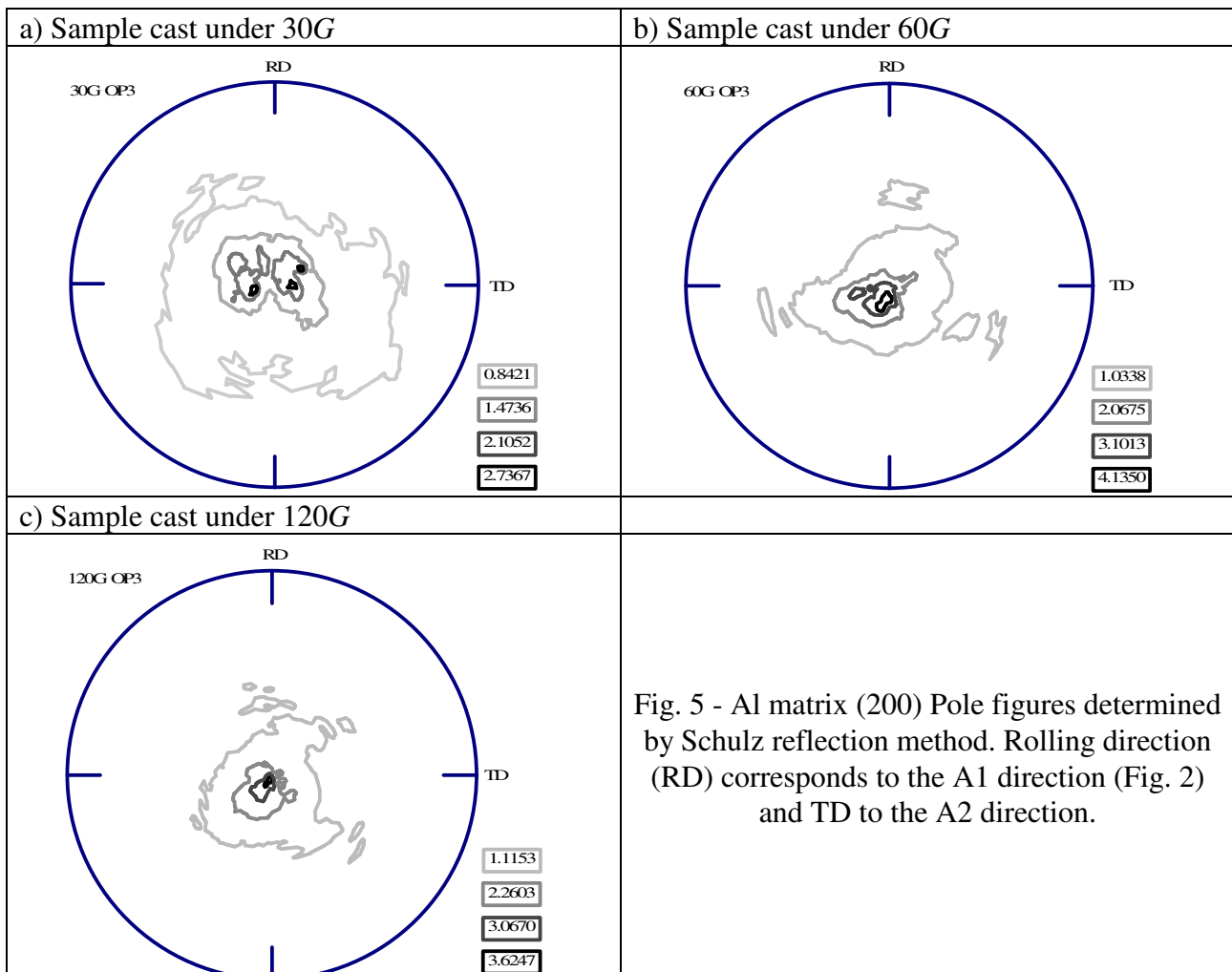
Table 3 – Hermans orientation parameter

Applied centrifugal force	Hermans orientation parameter		
	OP1	OP2	OP3
30G	0.839	0.775	0.019
60G	0.808	0.829	-0.074
120G	0.876	0.857	-0.164

**Texture of the Al matrix.** Aluminum matrix textures at the outer surface of the FGM specimens, along OP3, were studied by using the Schulz reflection method [6]. (200) Pole figures for each specimen, determined by this method, are presented in Fig. 5. As it can be seen non-random patterns appear in all pole figures, indicating a preferred orientation along the (200) plane for the aluminum matrix crystals. Furthermore, increasing the applied centrifugal force enhances this orientation effect.

Taking into account the results for particle orientation discussed in the previous section, a correlation appears to exist between  $\text{Al}_3\text{Ti}$  particle orientation and the preferred orientation of the Al matrix crystals. This correlation stands in agreement with the lattice correspondence found between the Al matrix crystals and the  $\text{Al}_3\text{Ti}$  particles in a previous study [8].

Considering that  $\text{Al}_3\text{Ti}$  particles remain, for the most part, solid during processing and have achieved their position as the solidification of the matrix engulfs them it is believed that the Al crystals' preferred orientation is dependent on the particles' orientation.





## Conclusions

In this study, Al-Al<sub>3</sub>Ti functionally graded materials (FGMs), were produced by the centrifugal solid-particle method and results concerning the characterization of Al<sub>3</sub>Ti particles and the aluminum matrix texture at the surface of produced FGM rings are presented.

- 1) Average intermetallic area fraction at the outer surface increases with higher applied centrifugal force.
- 2) Orientation of the intermetallic particles perpendicular to the centrifugal force direction was found along two of the observation planes, an effect that is increased with higher applied centrifugal force.
- 3) Al matrix crystals at the FGMs outer surface exhibit a preferred orientation on the (200) plane, indicating a correlation between the Al crystals' and the Al<sub>3</sub>Ti particles' orientation.

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